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Rf Structure of Superconducting Cyclotron for Therapy Application

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The superconducting cyclotron for neutron therapy application was studied. The characteristics of the accelerating cavity was measured using a full scale model.

KEY WORDS: AVF cyclotron/ Isochronous cyclotron/ Neutron therapy/ Radio therapy/

INTRODUCTION

Advantages of fast neutrons in therapeutical application are now widely recognized. Fast neutrons are generated by bombarding a thick beryllium target with high energy protons and deuterons. The AVF cyclotrons which deliver 50 MeV protons and 25 MeV deuterons are commonly used and are commercially available now. At the treatment usually rotational irradiation is taken to prevent an injury to normal tissue from the high LET effect of fast neutrons. The construction cost of both cyclotrons and isocentric irradiation installation are relatively high, so that the spread of neutron therapy is obstructed. A superconducting cyclotron for neutron therapy application was proposed by a Chalk River group.[1] This low cost design allows the installation to be a dedicated facility located in a hospital, and small size allows installations of the complete cyclotron in a rotatable gantry.

The design studies of the superconducting cyclotron based on this idea are going on at Kyoto University. The full scale model experiments for a rf structure of the cyclotron were carried out.

CYCLOTRON DESIGN

A three sectors AVF cyclotron with superconducting magnet was designed. The dees are mounted on $\lambda/2$ resonators in the valley of the magnet, and are connected at the center. The dees are driven from a single rf source in third harmonics mode. The cyclotron is shown in Fig. 1 and the main parameters of the cyclotron are shown in Table I.

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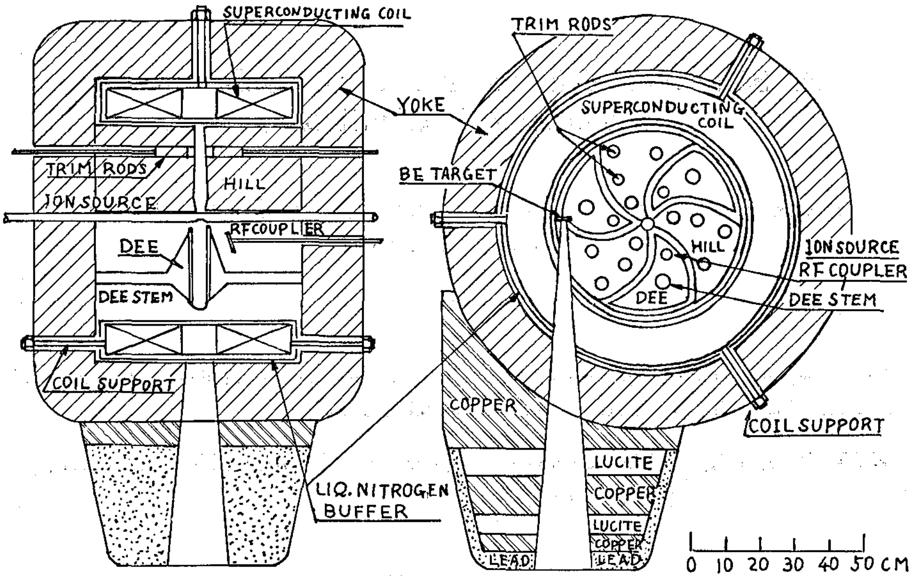

Fig. 1. Superconduction cyclotron for neutron therapy application.

Table I. *Main Parameters of Superconducting Cyclotron for Neutron Therapy*

Particle Beam Sepecifications	
Primary Beam	Deuteron
Particle Energy	30 MeV
Beam Current	50 μA
Secondary Beam	Fast Neutron
Peak Particle Energy	12 MeV
Dose Rate	
without Filter	170 rad/min
with Filter*	100 rad/min
Half-dose-depth	
without Filter	11 cm
with Filter*	13 cm
Accelerator Parameters	
Maximum Orbit Radius	25 cm
Focusing	AVF 3 sector
Magnet Pole	
Pole Radius	27 cm
Hill Gap	4~10 cm
Valley Gap	40~50 cm
Magnet Yoke	
Inner Diameter	82 cm
Outer Diameter	118 cm
Height	82 cm
Weight	~7 ton

Magnetic Field	
Hill	5.25 T
Valley	3.75 T
Average	4.5 T
Coil	
Superconductor	NbTi Fine Multiwire
Copper Ratio	1:1
Current Density	100 A/mm^2
Turns	6500/coil
Current	200 A
Ampere-turns	1.3×10^6/coil
Power Supply	DC 10 V, 200 A
Cooling System	Liq. He, 2 Phase, Circulating
RF System	
Resonator	3 Dee, $\lambda/2$ Coaxial
Dee Voltage	30 kV, 20 kW
Frequency	Fixed 100 MHz
Ion Source	PIG
Vacuum System	
Pressure	2×10^{-6} Torr
Pump	5000 l/s Cryopanel
Control System	Microprocessor Aided
Operation and Maintenance	4 persons

* 6 cm thick polyethylene.

RF STRUCTURE AND MEASUREMENTS

In Photo. 1 and Photo. 2 the full scale model for the rf structure and equipments for Q value measurements are shown. The size of the model is shown in Fig. 2. The resonant frequencies of the cavity were measured on the model changing the length of the cavity and the diameter of the dee stem, and the results are shown in Table II. It is estimated that the cavity length of 267 mm and the dee-

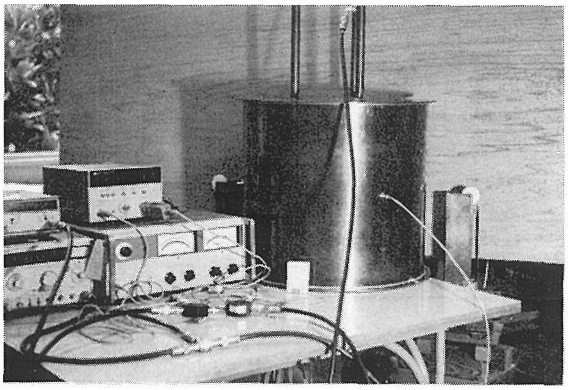

Photo. 1. Cavity model and equipments for Q-value measurements.

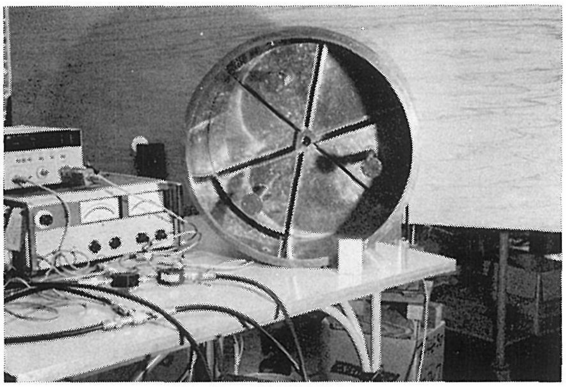

Photo. 2. Inside of the cavity. Dees, dee stems and cupper covers on the hills are seen.

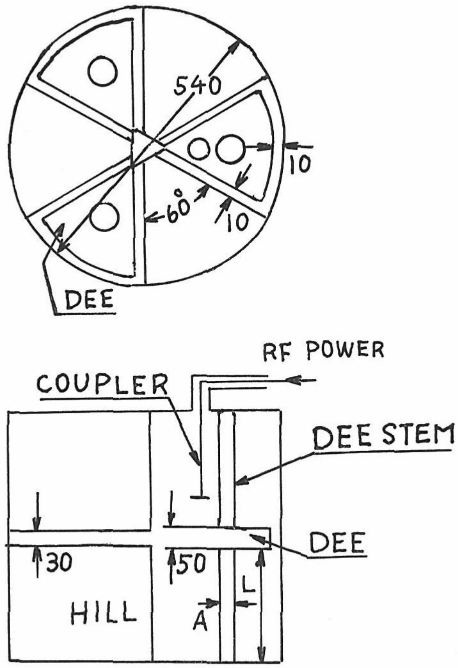

Fig. 2. Full scale model for rf structure of superconducting cyclotron. All are made of copper.

Table II. Resonant frequency of the cavity, A is the dee stem diameter and L is the cavity length

A	L	Frequency
20 mm	225 mm	108.9 MHz
50	278	122.9
30	278	104.1

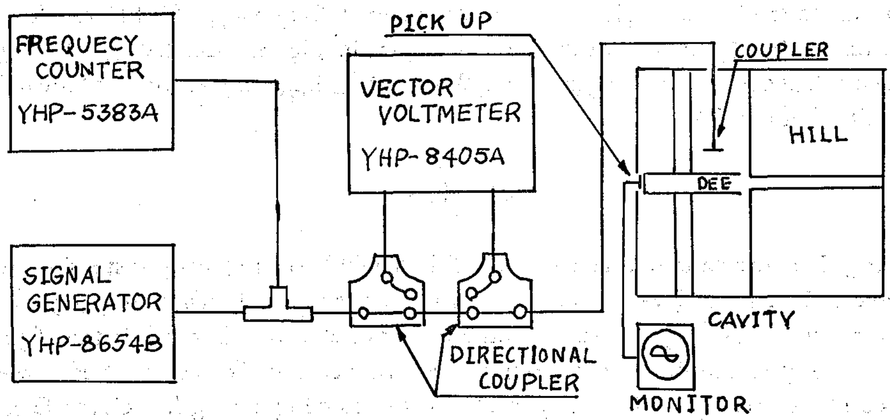

Fig. 3. Block diagram of Q value measurements.

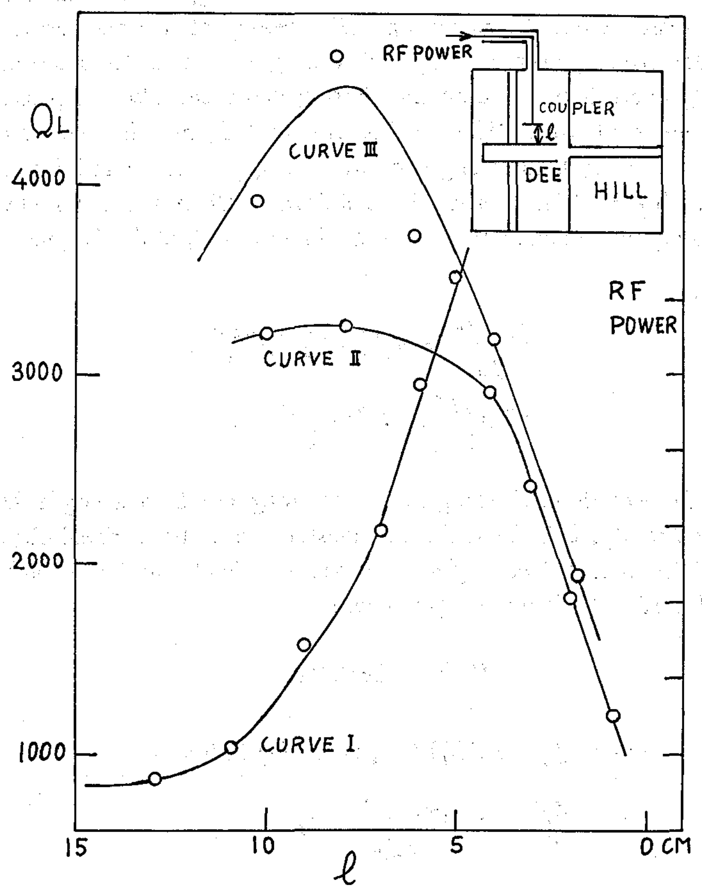

Fig. 4. Q_L as function of coupler-dee distance l. Curve I is rf power in cavity with constant input power. Curve II is Q_L at condition of curve I. Curve III is Q_L at different coupler condition.

stem diameter of 30 mm give the correct resonant frequency, 100 MHz. A block diagram of the Q value measurement is shown in Fig. 3. Loaded Q value, Q_L of a cavity depends on the coupling strength of a rf feeding coupler, and obtained from the following relation.

$$Q_L = \frac{f}{\Delta f},$$

where f is a resonant frequency and Δf is a width of frequency dispersion at resonance. Unloaded Q value, Q_0 is the asymptotic value of Q_L when coupling strength approaches 0. In Fig. 4 experimentl results are shown. Curve I is the rf power in the cavity as the function of coupler-dee distance l while the input rf power is constant. Rf power in the cavity relates to the coupling strength. Curve II is the Q_L measured at the condition of curve I. Q_L approaches 3200 when coupling strength decreases. When the coupler is connected with the cavity at different position, Q_L curve, curve III is obtained. Curve III shows that Q_L reaches maximum at l of 8 cm and decreases when l is increasing. The reason of this decreasing of Q_L is not obvious. However Q_0 may be suggested to be greater than the maximum Q_L value of 4500. Q_L curve is sensitive on the coupler shape and also the position where the coupler is connected with. The conclusion is that Q_0 may be greater than 5000.

The accelerating field strength of the dee gap is measured by the bead perturbation method.[2] The method is as follows. When a small metal ball is put into the cavity, the resonant frequency f_0 changes to f, and f is given by following relations.

$$\frac{f_0^2-f^2}{f_0^2} = 3(E_0^2-\tfrac{1}{2}H_0^2)\frac{4\pi r^3}{3}. \qquad \cdots\cdots\cdots(1)$$

$$E_0^2 \equiv \frac{\varepsilon E^2}{2U}, \quad H_0^2 \equiv \frac{\mu H^2}{2U}.$$

Where E is the electric field strength, H is the magnetic field strength, U is the stored energy in the cavity, ε is the dielectric constant, μ is the permeability, and r is the diameter of the ball. If we neglect the magnetic field and the second order of the frequency deviation the equation (1) becomes

$$\frac{f_0-f}{f_0} = 2\pi r^3 E_0^3. \qquad \cdots\cdots\cdots(2)$$

If we use the relation, $Q_0 = 2\pi f_0 U/W$, equation (2) becomes

$$\frac{\Delta f}{f_0} = 2\pi r^3 \frac{\pi f_0 \varepsilon E^2}{W Q_0}, \quad \Delta f = f_0 - f \qquad \cdots\cdots\cdots(3)$$

or

$$E^2 = \frac{\Delta f \times W \times Q_0}{2\pi^2 r^3 f_0^2 \varepsilon} \qquad \cdots\cdots\cdots(4)$$

where W is the energy dissipation per unit time in the cavity.

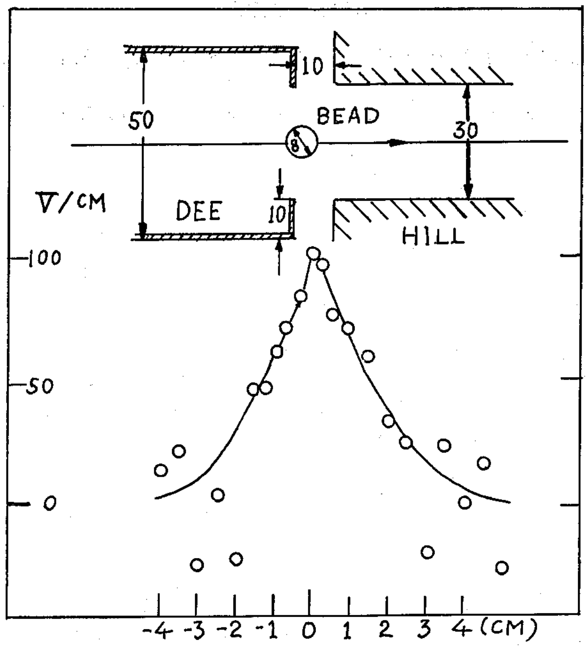

Fig. 5. Accerelating field distribution along dee gap measured with bead perturbation method.

The potential difference V at the dee gap is given by an integral of E across the gap

$$V=\int_{gap}Edx=\left(\frac{WQ_0}{2\pi^2 r^3 f_0^2 \varepsilon}\right)^{1/2}\int_{gap}(\varDelta f)^{1/2}dx \qquad \cdots\cdots\cdots(5)$$

Fig. 5 shows the experimental results. The bead used is a prastic ball of 8 mm diameter covered with aluminum. The potential difference V across the gap is

$$V=1.8\text{V}, \text{ when } W=52\mu\text{W}, \ Q_0=5000, \ f_0=110 \text{ MHz}.$$

It means rf voltage of 250V is obtained per 1W input power. The necessary rf input power W_p for 30 kV particle acceleration is

$$W_p=14.4 \text{ kW}.$$

A shunt impedance R of the cavity is defined as,

$$R=\frac{(6\text{ V})^2}{W_p}$$

Using the experimental values we get R=2.25 MΩ.

ACKNOWLEDGMENTS

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